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Spatially variable insecticide applications for early season control of cotton insect pests

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ABSTRACT

Our research has shown that cotton insect pests, specifically tarnished plant bugs, *Lygus lineolaris* (Palisot de Beauvois) (Heteroptera: Miridae) can be controlled early season in commercial cotton fields in Mississippi, USA, using spatially variable insecticide applications. Technology was developed for using GIS-based map scouting and a technique called the line-intercept method for obtaining low-level insect population counts in both rapidly growing areas of cotton and poorer growing areas. Using these population characteristics in combination with heuristic knowledge of the cotton fields and with the GIS maps, a spatially sensitive map could then be developed that could drive a spatially variable insecticide application for the control of the insect pest. We outline the steps needed to develop an automated technology for overcoming the time-sensitive events for early season control of cotton pests. This technology not only includes software systems for processing multispectral images to spatially variable insecticide application maps for spray controllers in the field but also high-speed wireless local area network (WLAN) technology for automated delivery of these controller application maps and for acquisition of as-applied and harvest maps from the field.

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1. Introduction

For the past seven years we have been evaluating the efficacy of multispectral imaging for use in developing GIS (geographic imaging systems) maps for scouting cotton pests, particularly in early season crop growth when insect populations are low and just beginning to grow. Typically, the pest populations at these stages of crop development are significantly below economic damage thresholds established by the Mississippi State University Cooperative Extension Service. This effort stems from the development of a statistically based scouting methodology called the line-intercept method, developed by Willers and Akins (2000), Willers et al. (1992, 1999). The line-intercept method was designed specifically to detect low-level insect populations in the field, and the method has shown superior efficiencies particularly in the time element over traditional insect scouting methodology (Bariola, 1969). Fig. 1 gives the basis for the line-intercept method. This method has shown that it is equivalent in accuracy to traditional methods while reducing the time element by as much as 40%. For pest management professionals, this literally means a 40% time savings that can be used to service additional client's acreage, putting more revenue into the scout's pocket. Multispectral imaging has made this methodology possible. Even more dramatically, imaging enables the management of early season insect pests in cotton using the maps derived from multispectral imagery. For a detailed description of the line-intercept method, see Willers et al. (1999).

2. Materials and methods

2.1. Multispectral imaging and NDVI maps

Four-band multispectral imaging is being used in our work. These have principally been collected using cameras mounted on fixed-wing aircraft. The four bands are in the blue, green, red, and infrared parts of the electromagnetic spectrum. Band one is centered on 485 nm (blue), band two on 560 nm (green), band three on 660 nm (red), and band four on 830 nm (infrared). Each band is typically 80 nm wide. After the image has been collected and corrected, a normalized displacement vegetative index (NDVI) is calculated producing a new image or map of the agricultural landscape. The correction process is the georectification of each image layer so that each pixel corresponds to the same location on the surface of the earth. Since we are using an NDVI-based process that is based on ratios of band layers, we do not have to correct the band layers for light quality. However, this process works only for the field from which the data were collected. One cannot take the information

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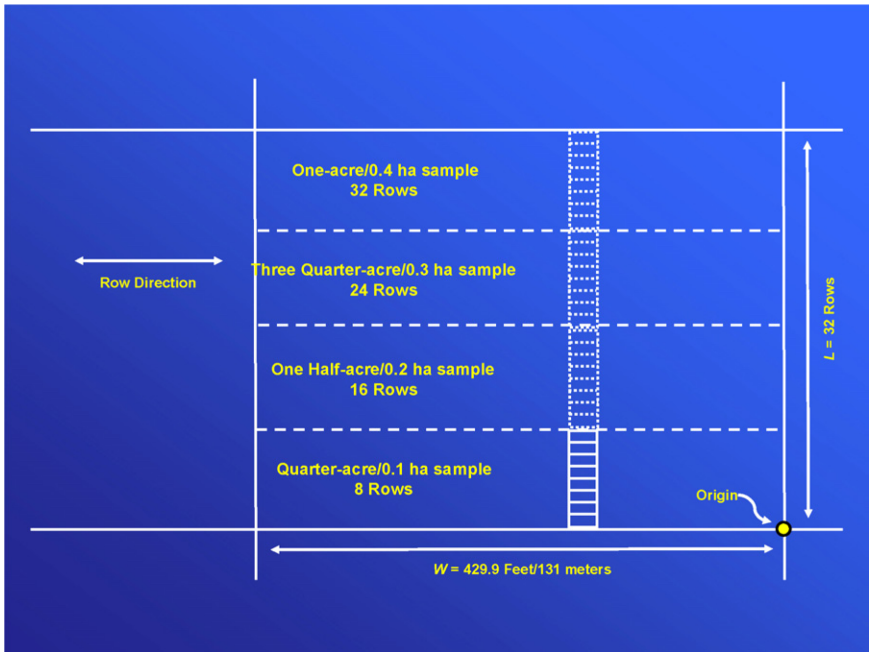

Fig. 1. Diagrammatic view of an 8 row, drop cloth transect line randomly placed within a 0.4 ha reference area. Present in dashline form are three additional 8-row sample lines that correspond to different scales of study as noted on the left. The baseline length (W) and the transect line length (L) define 0.4 ha (1 land acre) of land are based on 38 in. (0.96 m) row spacing planted with an 8 row planter.

from this field and apply it to another field located 20 km away. The same data have to be collected from that field and processed the same way described herein to obtain similar results for pest control.

An NDVI map (Schowengerdt, 1997) is derived from the multi-spectral image where

$$\mathrm{NDVI}(X, Y) = \frac{(\rho_{\mathrm{NIR}}(X, Y) - \rho_{\mathrm{RED}}(X, Y))}{(\rho_{\mathrm{NIR}}(X, Y) + \rho_{\mathrm{RED}}(X, Y))}. \tag{1}$$

X and Y represent the GPS coordinates of the pixel, ρ_{NIR} is the reflectance value of the near infrared pixel, and ρ_{RED} is the reflectance value of the red pixel in the four layer multispectral image. Together, all of the NDVI pixel calculated values generate a spatially registered map that is sensitive to differences in plant growth rate. The multispectral image must be of high quality and must be corrected by georectification. The next step in processing is to classify the NDVI map into four false-color grouping with colors indicating from best growing conditions to worst. The classified NDVI map is then used to develop the scouting map in which the line-intercept method is applied. In the scouting map, the image analyst selects a statistically significant number of GPS points in each color region to be sampled. The resulting map is then used in combination with a GPS (geographic positioning system) device to navigate to preselected areas of the cotton field where insect counts are made. Insect information and other knowledge are used to generate a new map that can drive variable rate insecticide equipment that applies insecticide as a spatial variable, that is, it is only applied where the insects are located. In cotton in early season conditions, one can literally take two steps from a pest-infested, rapidly growing area in the field to an area where the cotton has less favorable growing conditions and find no cotton pests. These conditions are the basis for utilizing multispectral image-based maps for scouting of fields for the cotton pests and applying spatially variable constant rates of pesticides for pest control. Multispectral images used in this study were collected by cameras installed on fixed-winged aircraft. While most of the images had a resolution of 1 m, some were collected at a resolution of 0.5 m. The higher resolution images were averaged down to 1 m resolution for use. Actual application tests on two commercial farms over the last three years have shown a potential savings of 60% of the pesticides used in conventional pest control programs.

2.2. Obstacles

While saving of time and material are significant and control of the pest has been achieved, there are significant problems in using this new technology. Multispectral imagery as a technique has been in existence for many years, but it has not been widely available commercially. Imaging from satellite sources can take 60–120 days from acquisition to delivery, or even longer. For this technology to be used for within-season crop management, rapid delivery is mandatory. Images of the subject cotton fields must not only be available in a timely manner, but they must also be of sufficient quality to be used. From the time the image is acquired to the time that the spatially variable insecticide is applied, no longer than 24 h ideally (48 h maximum) should elapse. The biology of the system is dynamic and insect populations in the field can shift in space, thus rendering the spatial insecticide application inadequate in controlling the pest and allowing an outbreak.

This obstacle is slowly being overcome by the commercial advent of aircraft equipped with multispectral imaging cameras that supply the needed images in a timely manner. Currently in Mississippi, images from the DuncanTech, Geovantage Digital Camera System, Positive Systems ADAR 5500 or Leica Geosystem ADS40 cameras[1] are available commercially.

Second, the image must be of high quality. This means that the georectification and orthorectification processes must produce images in which the pixels in the red, blue, green and infrared images are in alignment spatially and physically and true to the actual coordinate locations of the various features on the surface of the earth. Some vendors deliver the image with this process already completed. Next, the image must have good correction for ambient

[1] Use of trade names is for information purposes only and does not represent an endorsement of the USDA-ARS.

light at the time the image was acquired. This last aspect is not as critical as the first two since the NDVI process uses the ratio of difference between the infrared band and the red band to the sum of the infrared band and the red band. Thus the light quality issue tends to cancel out. However, one cannot transfer results to other areas distant from the local one if light quality has not been dealt with.

2.3. Detailed steps used obtaining spatial application map

After high quality images have been acquired, a number of processing steps are executed using a computer with at least a gigabyte of RAM and a hard disc with at least 40GB of free space. We have used a combination of ESRI ARCGIS and ERDAS Imagine software to analyze and process the imagery. Images may be delivered as a three-layer multispectral image.

The next step is to create an NDVI image by subtracting on a pixel-by-pixel basis and dividing by the summation on a pixel-by-pixel basis of the red and infrared images. This resulting image is then classified on a five color basis (Willers et al., 2009) using red, orange, yellow, green and blue colors of various hues and intensities to indicate rapidly growing areas (blues of the cotton field from which are growing the least (orange). Other color schemes are possible and over the years we have tried several schemes. We have learned several key points. First, if the number of classes is too large with too many unique colors, then the user is confused in proper interpretations of the map. If the number of classes is too few, then features of interest to the user in the field are obscured or lost in the binning of the classes and the colors assigned to them. The most useful schemes seem to be those which have a large number of classes (e.g. 25), that are color-ramped across an even multiple of major colors (e.g. 5 which is an even multiple of 25) where each major color is shown in different hues and intensities (e.g. Fig. 2). A processing logic similar to the latter point seems to balance the needs of not having too many colors or too few classes to obscure subtle changes in cotton crop phenology or field topography.

After classification, the resultant image is used as the map to which a statistically representative number of parsimoniously selected inspection points are assigned for each color region of the map (Willers et al., 2005, 2009). This process is executed repetitively for each field or management unit which is covered by a single foot print of the initial multispectral image.

The resulting map of the field or management unit is then used by the insect scout in combination with GPS devices to navigate to the assigned inspection points and employ the line-intercept method to determine the count of insects. Fig. 2 shows a typical scouting map generated by this process. The inspection points are chosen using the current and historical knowledge of the crop consultant about pest occurrences in this field in past years (in other words the consultant has knowledge of where pest outbreaks have occurred first and these areas should be scouted) and in combination with the NDVI information on the growing status of the crop in the field (similar colored areas need only be checked once in adjacent areas). After this information has been collected for all inspection points, it is returned to the image analyst. Based upon the linkages of the categorical labels to the original 26 classes (Fig. 2) and the maxima from enumeration distributions (Willers et al., 2009), it was possible to generate a pesticide prescription map (Fig. 2A). This particular map was prepared to keep the risk to the grower low but a higher cost due to needing more pesticide over a bigger area of the fields. For comparison at a later time, but with a higher level of risk to insect induced losses to the cotton crop, the prescription map shown in Fig. 2B was also prepared, based upon the knowledge that the two observers selected different locations which had an impact upon the maxima values from their respective complete enumeration distributions (Willers et al., 2009). Having the support of the analyses accomplished by Willers et al. (2009), there is evidence since that time to choose this map since the maximum statistic of the Best habitat for both observers was the worst. While the sampling evidence for the Good category and the Marginal habitat suggest that these areas could be left untreated. In actuality, neither map prescription was used because the grower elected to spray the entire field complex by air during the 2004 production season. To determine which of these 3 possible choices was best, requires applications of site-specific design and analysis concepts of Willers et al. (2008), where the consequences of these decisions upon yield are ascertained.

Both of these prescription maps are at the spatial resolution of the input imagery. The reader should note that either prescription map will also have to be rendered into an application map which drives the controller on the spray equipment. This translation step requires additional process requiring automation and results in an application map that has coarser spatial resolutions than the input imagery used to build the scouting map or either choice of a prescription map. Eventually, the application map is delivered and installed on the pesticide application equipment and the spray is applied to the field. An as-applied map (which may be different from the prescription application map) is collected and returned to the image analyst for archival and post-mortem analysis. The uploading of the controller specific-application map or the downloading of the as-applied file is also processing steps needing automation and wireless transfer.

This is the entire procedure required. Thus, we come to the final obstacle: processing time.

2.4. Automation

In the above scenario, an image analyst and a research entomologist actually tried to process and deliver as many application maps within the 48 h time limit from the point the multispectral images of the 4850 ha farm were delivered to them. This was essentially a manual type, point and click procedure. They slept only 3 h each night and were able to generate application maps for 1200 ha by manual steps using ARCGIS and Imagine software for image analysis and translate in the final step to the controller-compatible image using either the SST Development Group, Inc.'s SSToolbox or the Ag Leader Technologies, Inc.'s Spatial Management System (SMS) software.

Representatives of the USDA-Agricultural Research Service contracted with Leica Geosystems to automate the above procedure to reduce as much as possible the time required to process and deliver scouting maps and then to process and deliver application maps. Fig. 3 shows the six phase procedure: (1) acquire images, (2) subset images into working units, (3) compute plant vigor, (4) create scouting map, (5) determine the prescription, and (6) apply the prescription.

Working with Leica Geosystems, we found that we only needed two software systems: Imagine would be used for steps 1 through 5 and either the SST Development Group, Inc.'s SSToolbox or the Ag Leader Technologies, Inc.'s Spatial Management System (SMS) software would be used to generate the application map specific to the spray controller. We also found that by using the Imagine advanced features and scripting language that our objective of automating essentially all of the image processing procedures could be accomplished, and that indeed the process could be greatly enhanced from a speed-of-processing viewpoint. As an example, one of the steps that took up to 3 h of manual operations for generating 1200 ha of application maps on the test farm was reduced to 10 min of processing time using Imagine scripts running on the same computer. Today we have automated almost 95% of the manual steps with one project still ongoing. Essentially we believed that 98% of the

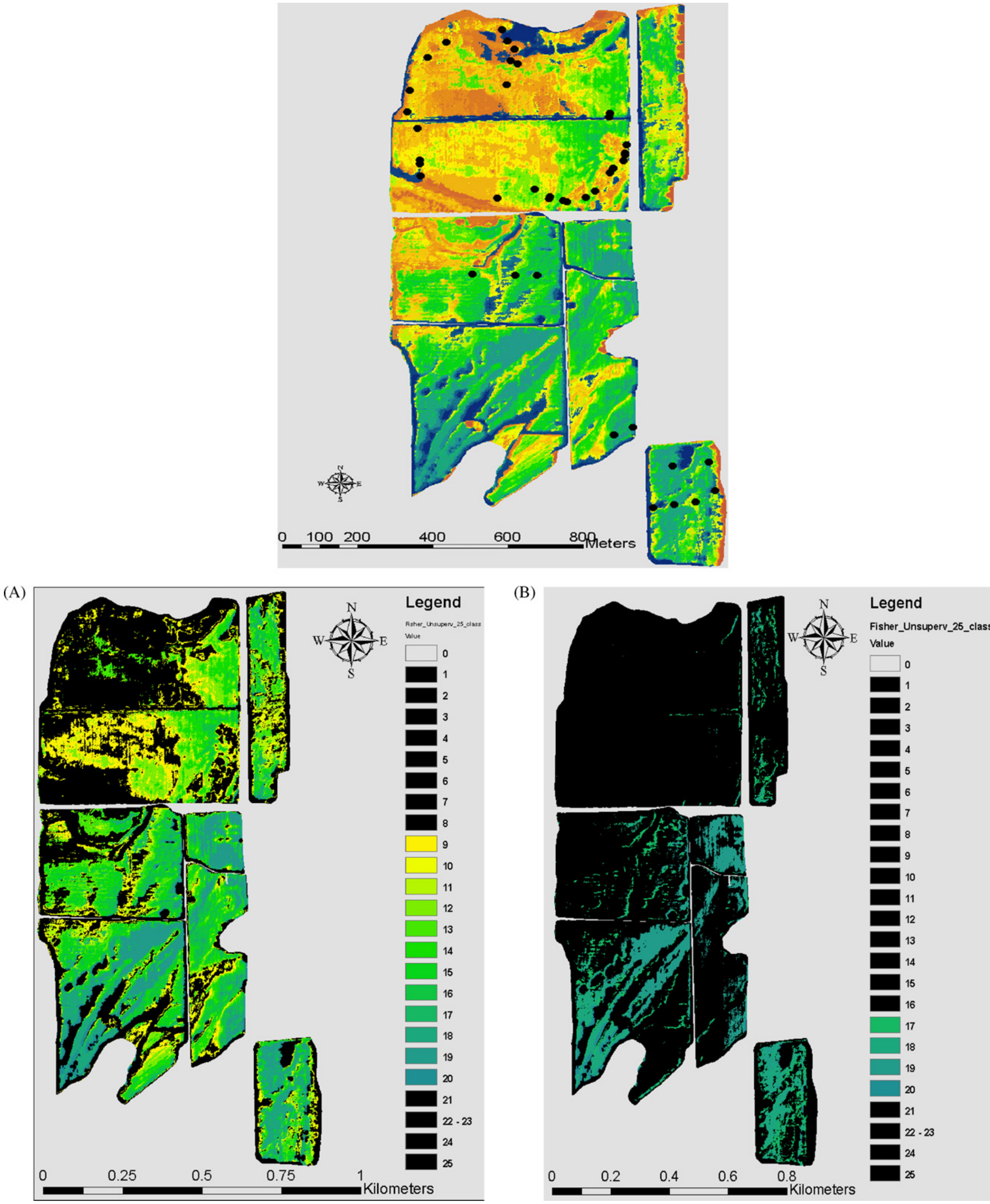

Fig. 2. Multispectral image of several cotton fields with inspection points identified for sampling as indicated by the black dots. (A) Panel showing the relationship between the original 26 habitat classes and a low risk, higher cost prescription map. Pixels assigned to the black color are in the no spray decision category. (B) Panel showing the relationship between the original 26 habitat classes and a high risk, lower cost prescription map. Pixels assigned to the black color are in the no spray decision category, leaving only the most vigorous populations of cotton plants (the blue hues) to be treated for an insect pest.

processing required to go from a multispectral image to an application map via automation has been accomplished. By automating this procedure by using either faster computers or multiple computers by dividing tasks, we can process multispectral images to NDVI maps to scouting maps and finally to application maps for 5–10,000 ha farms easily meeting the time deadlines. In combination with the line-intercept scouting methodology which reduces the time required for scouting, these methodologies can now be brought to bear on early season pest control meeting the 48 h time limitation.

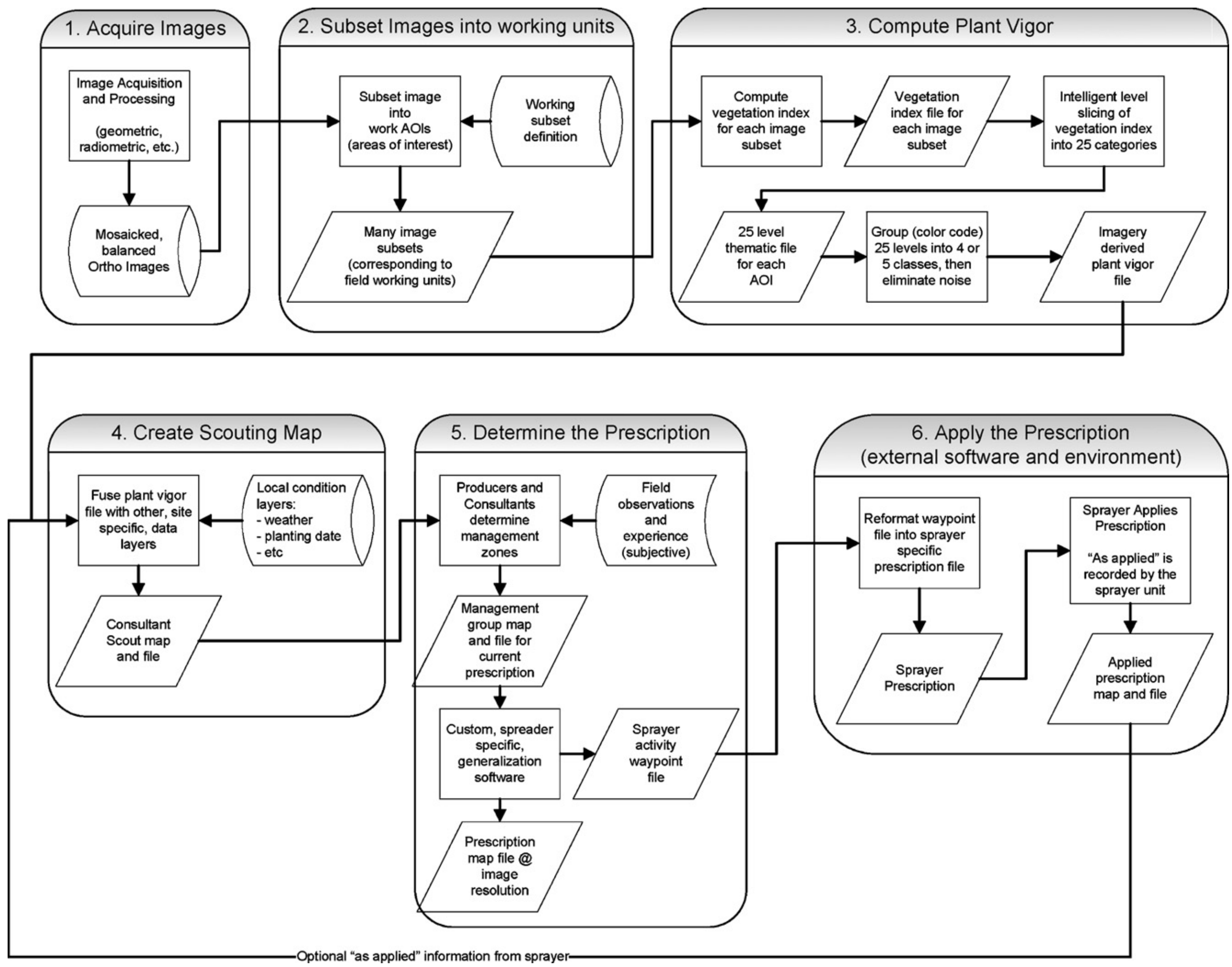

Fig. 3. Flow diagram for automation of image processing steps for creating application prescription for spatially variable insecticide.

2.5. The delivery problem

Over the last 15 years, the use of wireless data technology has expanded at an ever-increasing rate (Geier, 2002). The availability of license-free spectrum for public use has been a large contributing factor in this technology area (Code of Federal Regulations, 1985). While the initial use of the Industrial–Scientific–Medical (ISM) license-free bands was solely intended for indoor use, innovators have greatly extended the initial foreseen applications from rapid indoor transmission of data to new outdoor applications, called WI-FI. The outdoor applications have come over the last five years and have multiplied greatly with the adoption of industry standards that have led to a sharp reduction of equipment costs further enabling usage. Today we are at the threshold of a new era in high-speed wireless networking. A new standard has been developed by industry to specifically address the needs for outdoor, high-speed wireless communication with non-line-of-sight capability with both fixed and nomadic applications. Several hundred companies have announced their support for this new standard called WIMAX, including industry giants such as Intel, Motorola, and Nokia (Sweeney, 2004). As economies of scale develop, high-speed wireless Internet communications should become cheap and ubiquitous in rural America.

As this technology becomes ubiquitous, it can serve to overcome another vexing problem hindering the use of multispectral image-based precision agriculture. That problem is framed by the question: How can we transmit multi-megabyte files to and from equipment in the field? When fields consist of several hundred hectares in a single management unit, the application map files that drive the controllers for precision application of seeds and farm chemicals can easily be several megabytes in size. The reason for this is that manufacturers of application control units have chosen to collect and use information in the raster format rather than in the polygon format. Certainly, polygon formatted data to direct application sprays would be very compact and take minimal storage space. Raster data are very dense and require large storage spaces. Harvest maps and as-applied maps collected from these fields can be from hundreds of kilobytes to megabytes in size. Currently, the method for delivery and pickup of these data files is to use a computer-knowledgeable person to hand-deliver and collect PC cards that the controllers use. It has been our experience that up to 3 h per day on a large commercial cotton farm can be required for this process. Care must be taken to deliver the PC card to the right equipment, to remove carefully the current PC card and to carefully insert the replacement PC card. If the receptacle for the PC card is damaged, the entire controller must be sent back to the factory to fix this problem, necessitating either the loss of time in precision farm operations by requiring other controller equipped equipment to perform the operations of the damaged controller equipment or the carrying of spare controllers that results in additional cost to the grower.

2.6. Demonstration WLANs on two farms

Wireless local area network technology can solve the map delivery and acquisition problem. Use of landline modems which can operate up to a theoretical 56 kbaud simply cannot handle megabyte size files with any reasonable expectation of timely delivery. This is especially true in the rural US where actual modem rates sometime fall as low as 12 kbaud due to poor line quality (personal experience). If one byte is dropped the whole file has to be transmitted over again. Current technology can connect farms either via satellite, General Packet Radio System (GPRS) or Enhanced Data rates for GSM (EDGE) cellular radio system, or digital point-to-point data links. Satellite can deliver 2–3 mbps downlink and up to 800 kbps uplink. The cellular technology can deliver typically 600 kbps down and 200 kbps up. Point-to-point links can easily deliver bidirectional high-speed links up to 20 mbps or more full duplex. Current technology exists which allows small farms from several hundred hectares to large farms over 10,000 ha to have high-speed, reliable digital communication between the farm headquarters and multiple equipment pieces in the field. By taking advantage of WLAN technology, one can be assured to deliver multi-megabyte controller application maps directly to the application machinery for which the map was intended, eliminating completely the problem of misdelivery.

We have demonstrated the effectiveness of WLAN equipment on two demonstration farms in Mississippi. The first farm would be classified as a small cotton farm located in Noxubee County, MS, USA. The Paul Good Farm consists of 650 ha of contiguous farm land as shown in Fig. 4. Fig. 5 shows the location of the farm headquarters with the WLAN base station and the three repeater stations. This system operates at a system speed of 3 mbps data rate with a user data rate of 2 mbps aggregate. With the three repeater stations, approximately 80% of the farm is under coverage of the WLAN.

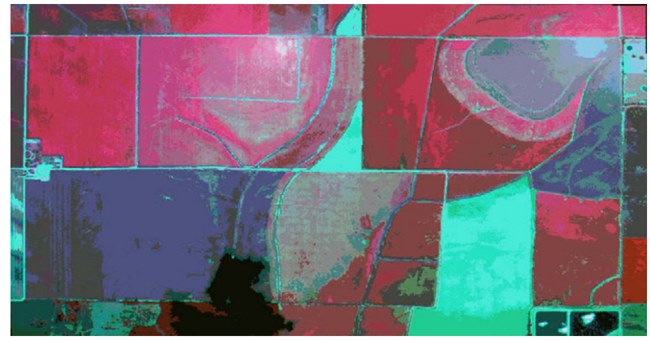

Fig. 4. Multispectral image of the Paul Good Farm, Noxubee Co., MS, USA.

Access to the Internet is provided by a Direcway satellite system with a downlink speed from 500 to 1000 kbps and an uplink speed from 75 to 150 kbps. With the high-speed downlink, the Internet connection is more than sufficient to deliver application and scouting maps to the base station and field equipment. The equipment used here is the Alvarion Breezecom and BreezeAccess II frequency hopping spread spectrum (FHSS) outdoor radios that operate in the license-free 2.4 GHz spectrum. The BreezeAccess II radios are used in the base station, with the antenna mounted on the apex of the tallest barn, and to communicate to the repeater stations. At the repeater stations, the Breezecom radios using sectorial antennas focused inward to the farm allow communication to all machinery in the field either stationary or moving up to 80 kph without loss of data. One of the repeater stations is shown in Fig. 6.

The second farm upon which we demonstrated the WLAN technology is Perthshire Farms located in Bolivar County, MS, USA in the Mississippi Delta bordering the Mississippi River. Perthshire Farms

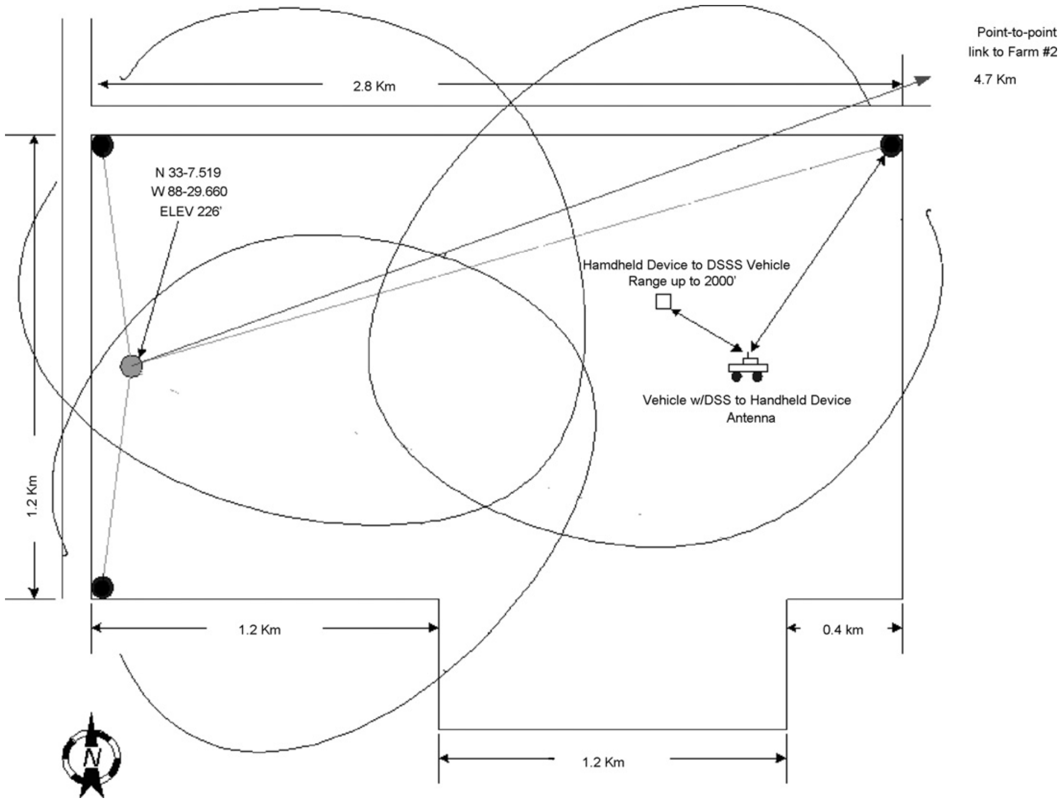

Fig. 5. Coverage of the Good Farm using repeater stations as basis for the wireless local area network and base station to provide connectivity to the base computer and satellite Internet.

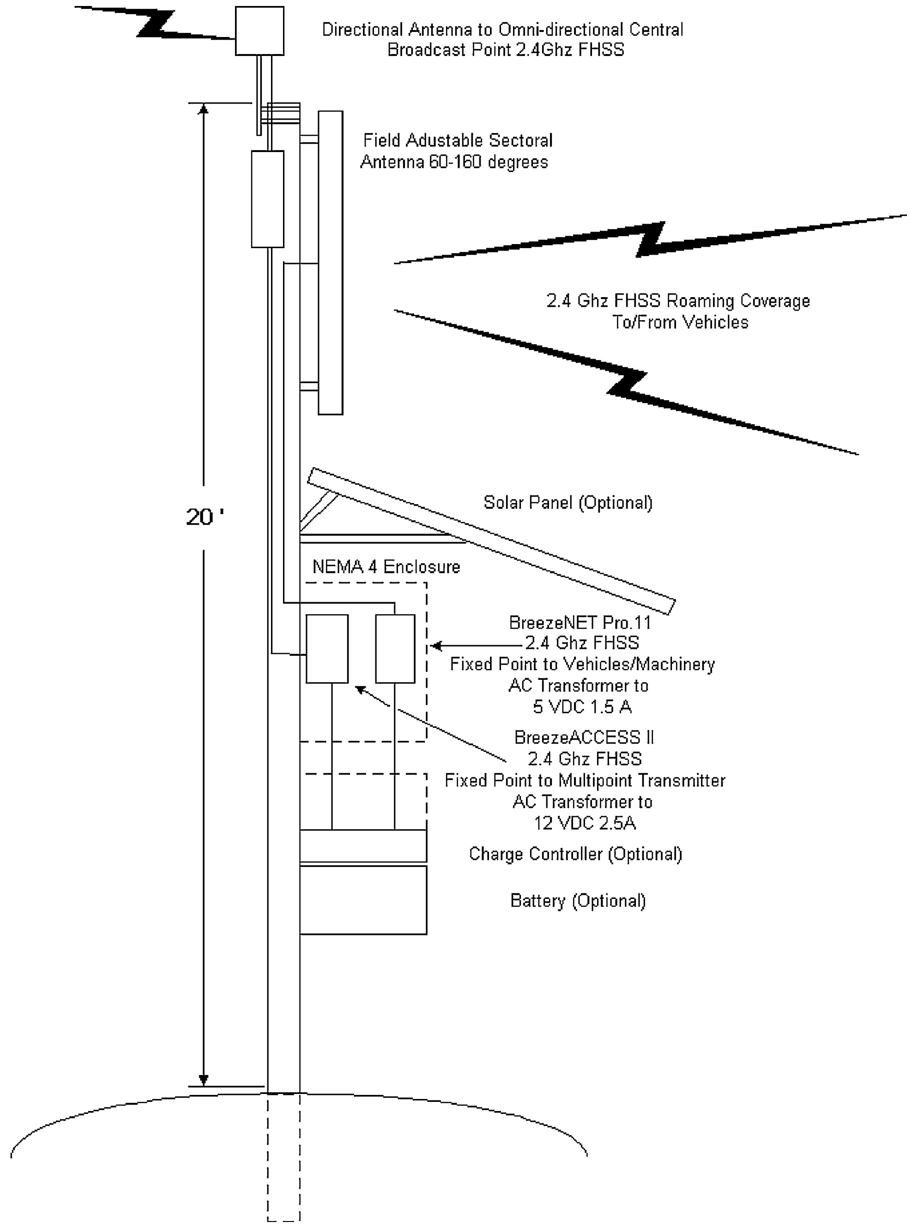

Fig. 6. Schematic of the repeater station equipment showing radios, solar panel, battery, high gain antenna and sectorial antenna.

can be classified as a large commercial cotton operation with over 220 fields, non-contiguous, with tree lines separating fields in over 4860 ha of farm land. The Good Farm was contiguous with no trees allowing the use of line-of-sight (LOS) 2.4 GHz FHSS radios. The tree lines on Perthshire Farms negate the use of this technology. Instead, we used the 900 MHz WaveRider 4000 direct sequence spread spectrum (DSSS) system for the base-station-to-repeater-station communication network that can provide up to 4.8 km of non-line-of-sight (NLOS) operation with a system speed of 3 mbps and a user aggregate data rate of 2 mbps, the same as the Alvarion BreezeAccess II radios. As before, Alvarion Breezecom radios were used in the repeater stations to provide coverage of the equipment in the field, because of their capability to provide continuous communication with either stationary or moving equipment. The base station was located at the farm headquarters but the antenna for this system had to be mounted on a 50 m tall wire-guyed tower to assure clearance of all structures and trees at this location. To provide coverage for the farm we used 7 repeater stations whose locations are shown in Fig. 7. One of the repeater stations is shown in Fig. 8. Three of the repeater stations are located at the base station antenna mounted at the 33 m level on the base station tower using 120° sectorial antennas giving 360° coverage from this point.

3. Results

In 2008, there were 9.47 million acres (3.67 million hectare) of cotton planted in the United States and in 2009 there is forecast of a total planting of 8.11 million acres (million hectare) (NASS, 2009). For the MidSouth area the total cotton planted in 2008 was 1.88 million acres (0.76 million hectares) and in 2009 the forecast is for 1.44 million acres (0.58 million hectares) to be planted. This research was carried out in the MidSouth region. According to the work of Snodgrass et al. (2006) for growers in the Mississippi Delta, over the period of 1999–2001, control of the tarnished plant bug required an average of 4.2 insecticide treatments per season using the traditional blanket spray approach at a mean cost of $72.44 per hectare or $17.25 per hectare per treatment.

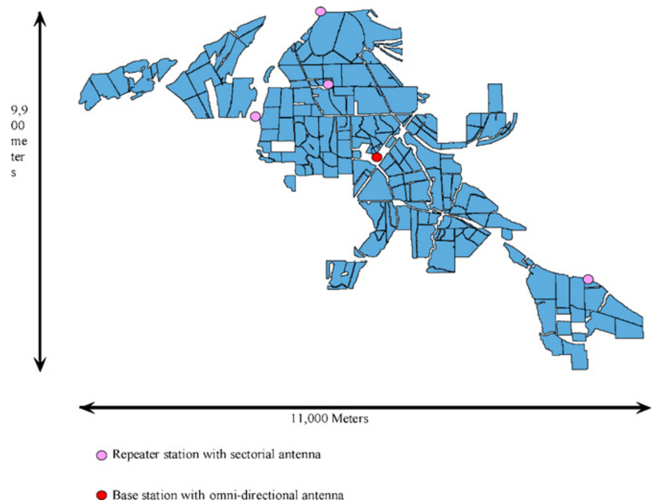

Fig. 7. Map of Perthshire Farms with red dot indicating location of base station and pink dots indicating location of repeater stations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

In the two tests that were run using our early season control methodology, only one insecticide treatment was required for the Paul Good Farm in Noxubee County, MS and for the field treated on Perthshire Farms in Bolivar County, MS. After the treatment was applied, no tarnished plant bugs were detected on the Paul Good Farm for the remainder of the growing season and very low numbers were detectable on Perthshire Farms test field. The key to the success of these two tests was the timing of the insecticide applications which led directly from using the line-intercept scouting methodology directed by using the GIS maps to delineated sampling points in the fields, rapid collection of these data, production of pesticide application maps which are GIS driven, and delivery of these maps to the application equipment for pesticide application. We were more successful on the Paul Good Farm because the size of the cotton acreage was relatively small and required less processing time and we were more able to meet the optimum 24 h turn-around time. We were relatively less successful (tarnished plant bugs were detected later in the season but did not require intervention) on Perthshire Farms because of the larger acreage involved required more processing time and we exceeded the 24 h optimum but met the 48 h deadline. This shows that more effort has to be expended in speeding up the methodologies described herein principally by the automation of the software processes and by ensuring rapid delivery of application maps.

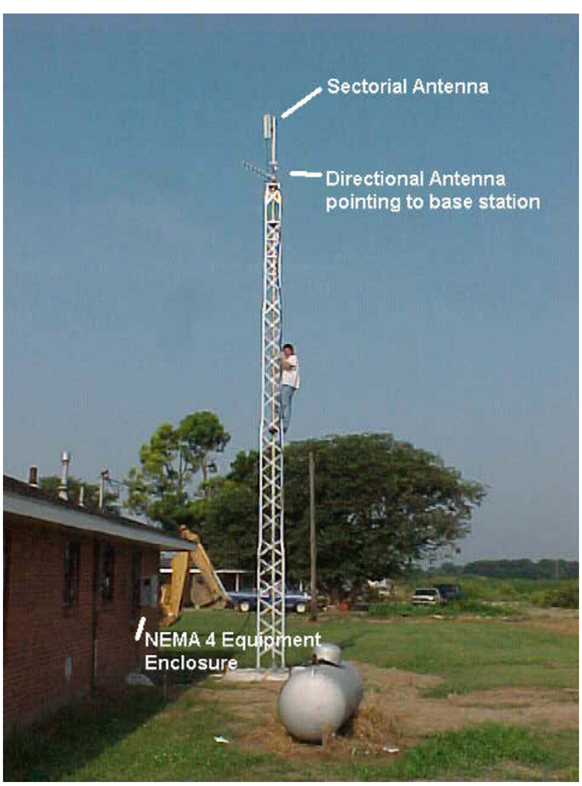

Fig. 8. Photograph of repeater station showing configuration of yagi high gain antenna for communication with base station and 160° sectorial antenna for communication with moving equipment in the field.

In the figure of merit of cost of $17.25 per hectare for a single blanket application, this cost includes the cost of application and materials. For the MidSouth area alone this represents a potential savings of $32 million for 2009 if the methodology was universally adopted. However, growers would have to invest in precision application equipment which would be GPS driven to take complete advantage of the methodology. In this case a blanket application would not necessarily be the rule and even more potential savings could be implemented by making a spatially variable application: spray where the tarnished plant bug is and not where he is not. This case is shown in Fig. 2A and B where two scenarios were prepared. In Fig. 2A a low risk options for early season control of the tarnished plant bug was prepared. One can see that most of the acreage was involved and very little could be gained from a spatially variable insecticide application. In this case a single blanket aerial application was actually made. However, in Fig. 2B a higher risk scenario was developed. One can see that very little of the acreage would have to be sprayed under this scenario. In hindsight, the Fig. 2B scenario was the correct one that should have been used and would have resulted in considerable savings of materials.

4. Conclusions

To date we have shown that these radio systems can be used to deliver application maps directly to farm equipment which used the maps to make precision applications. We have also shown that we can collect as-applied maps and harvest maps from the farm equipment generating these maps. Because the radios have to be assigned unique Internet Protocol (IP) addresses in order to operate in the WLAN, this unique address can be used to assure that each piece of equipment is sent the correct data to use in the controller. Indeed, the controller will not operate in the wrong geographic location. All these can be accomplished at electronic speeds ensuring accuracy, preserving equipment, and saving many man-hours of time during time-critical operations for early season pest control in cotton.

When insecticide is applied using the spatially variable method, our studies have shown that a savings of up to 60% of traditional blanket insecticide for tarnished plant bug control can be realized while maintaining control of the plant bug. By automating the procedures required to go from a multispectral image to a scouting map and then proceeding to an application map for early season control of cotton insect pests, a complicated and time consuming technology has been simplified and brought to delivery. The principal limitation of this technology is the 24/48 h window of opportunity. Up to $250 per hectare is spent each year by U.S. cotton farmers on the cost of insecticides alone using traditional blanket sprays. By using this technology, more profit for the grower and a cleaner environment would result. In addition, by combining this methodology with line-intercept scouting and using WLAN delivery technology, we can easily meet the time requirement, while providing up to a 40% improvement in scouting efficiency.

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